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Exploring the Future of Organoid Intelligence in Agricultural Applications

Lalson Wesly Johnson[1] and Kabilan[2]

[1]PhD student, Division of Nematology, Indian Agricultural Research Institute, New Delhi –110012, India

[2]PhD student, Division of Bioinformatics, Indian Agricultural Research Institute, New Delhi- –110012, India

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Abstract:

Organoid Intelligence (OI) represents a groundbreaking interdisciplinary field focused on the application of three-dimensional brain organoids—lab-grown clusters of human brain cells—as a novel form of biological intelligence. These organoids, derived from human stem cells, emulate certain structural and functional aspects of the human brain, exhibiting key characteristics such as neuronal activity and synaptic connections essential for learning and memory. This review explores the potential transformative impact of OI in agriculture, highlighting applications such as biosensors for environmental monitoring, biofeedback systems for optimized growth conditions, and advanced biotechnology for crop engineering. Organoid-based biosensors can dynamically interpret biological signals to enhance plant health monitoring and early disease detection, while biofeedback systems can facilitate tailored agricultural practices by responding to plant stress signals. Moreover, integrating OI into crop biotechnology could lead to the development of self-regulating crops capable of autonomously managing their resources and defense mechanisms. Despite these promising applications, the field faces significant ethical and practical challenges, including concerns regarding the use of brain organoids in non-medical contexts and the technological hurdles of scaling OI for real-world agricultural implementation. As research in OI progresses, breakthroughs may pave the way for innovative agricultural technologies, but the timeline for practical adoption remains uncertain. Overall, OI holds the potential to significantly enhance sustainability and efficiency in agriculture, with the advancement of biohybrid systems serving as a critical bridge to realize these innovations.

Introduction:

Organoid Intelligence (OI) is an emerging interdisciplinary field that explores the potential of using three-dimensional brain organoids—small, lab-grown clusters of human brain cells—as a form of biological intelligence. Derived from human stem cells, these organoids mimic certain aspects of the brain's structure and function, although they are much simpler than a fully developed brain. Comprising clusters of neurons that can generate electrical impulses and form synaptic connections, brain organoids exhibit characteristics critical for learning and memory. A key aspect of OI is the ability of these neuronal clusters to learn and store information, similar to how neurons in the human brain communicate and form connections. Researchers aim to investigate processes like synaptic plasticity in organoids, which may allow them to process information in ways akin to natural neural activity, potentially functioning as biological computers (Hartung *et al.*, 2024; Smirnova Lena *et al.*, 2023).

Biological computing, or biocomputing, has the potential to surpass traditional silicon-based computing and artificial intelligence (AI) in speed, efficiency, and power while consuming significantly less energy. The advancement of OI requires scaling up current organoid models into more complex and durable three-dimensional structures, integrating essential learning-related cells and genes, and connecting them with next-generation input/output devices and AI systems.

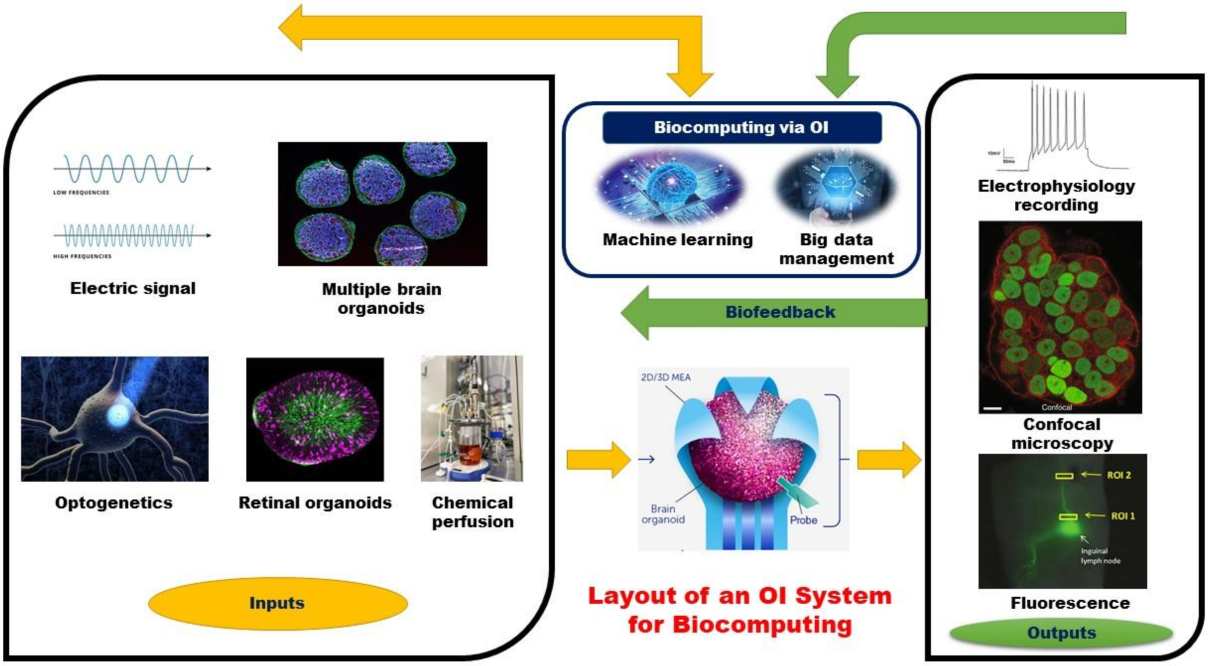

Fig. 1. Framework of a Biological Organoid Intelligence System (Smirnova Lena *et al.*, 2023)

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This will necessitate the development of new models and technologies for effective interaction and data management. Beyond computational applications, OI research may enhance our understanding of brain development and lead to treatments for neurological disorders such as dementia. However, to ensure responsible progress, OI development must be guided by an "embedded ethics" framework, involving collaboration among ethicists, scientists, and the public to address ethical concerns (Kim *et al.*, 2023). Importantly, OI differs from traditional AI, which relies on algorithms and data processing. While AI operates through digital artificial neural networks, OI utilizes living cells that can mimic natural brain functions, offering a unique perspective on intelligence and computation.

The Potential of Organoid Intelligence in Transforming Agriculture

- **Biosensors and Environmental Monitoring:** Organoid-based biosensors hold the potential to revolutionize plant microenvironment monitoring through advanced, biologically-driven mechanisms. Unlike traditional sensors that depend on physical or chemical interactions, organoid intelligence could interpret intricate biological signals, such as variations in plant secretions, shifts in soil microbial activity, or the presence of airborne chemical compounds. These biosensors could function as bio-neural networks, capable of dynamically adapting to environmental changes with greater sensitivity and precision. For instance, such sensors might detect early indicators of plant diseases or nutrient imbalances before they manifest visually or are detectable by conventional tools. Continuous real-time monitoring could enable the early identification of stress factors like drought, pest infestations, or nutrient deficiencies, mitigating their impact on crop yield. Additionally, organoids could potentially learn from recurring environmental patterns, enhancing their predictive accuracy over time by recognizing trends in soil chemistry or plant behaviour. By facilitating the precise monitoring of plant and soil health, these biosensors could optimize the application of fertilizers, pesticides, and water, contributing to more sustainable agricultural practices with reduced environmental impact.
- **Optimized Growth Environments using biofeedback Systems**: In this context, organoid-based biofeedback systems could act as an interface between plants and agricultural infrastructure, offering a sophisticated approach to precision farming. Plants naturally release biochemical signals when subjected to stress factors such as

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water scarcity, excessive heat, or nutrient deficiencies. An organoid-based system could interpret these signals and initiate specific actions within the farm's automated systems, such as adjusting irrigation, fertilization, or shade coverage. Over time, this feedback system could evolve, learning from the plant's biochemical cues to refine care strategies and account for individual plant needs. This would ensure that each plant receives tailored inputs, reducing resource waste while maximizing yields. Once implemented, such systems could function autonomously, significantly reducing labour demands and enhancing operational efficiency. By fine-tuning the application of water, nutrients, and pesticides, the system could also reduce the environmental impact of farming. Unlike conventional AI systems driven by pre-programmed algorithms, organoid-based systems have the potential to "learn" from previous experiences and adapt dynamically, improving decision-making processes and advancing precision agriculture.

- **Biotechnology and Crop Engineering:** In this scenario, organoid intelligence could be harnessed in biotechnology to create more intelligent, self-regulating crops. Through bioengineering, plants could be endowed with enhanced capabilities, such as autonomously managing their nutrient uptake, optimizing growth patterns, or activating defence mechanisms against pests. By integrating organoid intelligence into the plant's genetic architecture, scientists may develop crops capable of "sensing" threats from pathogens or pests and triggering pre-emptive defence responses. This approach could also include the development of crops with built-in biosensors that allow them to monitor their own environmental conditions and "communicate" with external systems for optimal care and management. Such crops would have greater resilience to extreme conditions and improved pest resistance, potentially reducing the reliance on chemical treatments. Furthermore, these crops could autonomously optimize the use of resources like water and nutrients, minimizing the need for irrigation and fertilizers. With crops that are more self-sufficient and adaptive, agriculture could become significantly more sustainable, decreasing chemical inputs and reducing labour demands, while improving overall productivity.

Ethical and Practical Challenges

While the potential applications of organoid intelligence (OI) in agriculture are promising, the field presents several significant ethical and practical challenges. One key concern is the ethical implications of using brain organoids for non-medical purposes, such as

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farming. As organoids become more advanced, questions may arise about their level of "intelligence" and whether their use could constitute exploitation or harm. Defining the ethical boundaries for such biological systems is a complex issue that will need careful consideration. Furthermore, OI technology is still in its early stages, and scaling it to practical applications in agriculture could take decades. The performance of these biological systems in open and variable environments like farms remains uncertain, raising questions about their robustness and reliability. The agricultural sector, traditionally cautious about adopting new technologies, may also be slow to embrace biohybrid systems due to concerns over public trust and the potential risks associated with introducing living systems into the food supply chain.

In addition to these concerns, the cost of developing and deploying OI-based systems is likely to be high, particularly in the initial phases. This could deter farmers from adopting the technology unless it proves both affordable and demonstrably beneficial. Widespread adoption may hinge on significant cost reductions and clear evidence of the system's ability to improve efficiency and sustainability in farming practices.

Conclusion

Although the convergence of organoid intelligence and agriculture is primarily speculative at this stage, the potential applications—spanning biosensing, environmental monitoring, intelligent decision-making, and biotechnology—hold great promise. As research in organoid intelligence progresses, we may witness significant breakthroughs that could be tailored for agricultural purposes. However, substantial challenges and an unclear timeline for development persist. The advancement of biohybrid systems may serve as a crucial intermediary, facilitating the incorporation of biological learning and decision-making into cutting-edge agricultural technologies.

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